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NILS SUNDIUS

**Felspar and its Influence on the Reactions  
in Ceramics during Burning**

*Swedish Contribution No. 7*

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FELSPAR AND ITS INFLUENCE ON THE REACTIONS  
IN CERAMICS DURING BURNING

by

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Alkali felspar is the most common flux in ceramics. It is very suitable for this purpose because it forms, together with quartz, mixtures that melt at relatively low temperatures and have within a considerable temperature interval a high viscosity, counteracting the deformation of the objects in the kiln.

The name felspar when used in connection with ceramic working may generally be associated with a potassium felspar, but the name includes more varieties. Apart from the rare barium felspar (celcian), which plays no role in this connection, three different varieties with different compositions and rather complicated interrelations can be distinguished, namely potassium-, sodium- and lime-felspar, of which the two first named and mixtures of them are generally named alkali-felspars. All three have a certain external property in common by means of which they can be distinguished from quartz. This is the presence of cleavages along two planes, perpendicular or nearly perpendicular to each other (P and M in fig. 1), allowing the felspar to be divided along even and bright surfaces, whereas quartz is split up along irregular and uneven fractures. The hardness is also somewhat lower in felspar than in quartz (6 in the former and 7 in the latter).

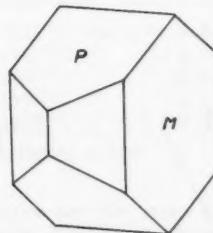


Fig. 1. Felspar crystal

Potassium felspar. The formula of the pure K-felspar is  $K_2O \cdot Al_2O_3 \cdot 6 SiO_2$ , corresponding to 64.7 %  $SiO_2$ , 18.4 %  $Al_2O_3$  and 16.9 %  $K_2O$ . The colour is generally reddish, but can be white, grey or grey-brown. In one kind of K-felspar, named amazonstone, the colour is green. It can contain some small amount of rubidium, but otherwise the composition is the same as in those with more usual colouring. Natural K-felspar can have acquired different crystallographic properties according to the circumstances prevalent during the crystallization, but these differences have more theoretical than practical significance. The two most important modifications are orthoclase and microcline. The first named is monoclinic with a right-angle between the two cleavages. The microcline is triclinic and the cleavage angle is  $90^\circ 30'$ . The oblique angle in the microcline makes possible a twinning in the felspar of the same kind as that described below for albite, but the twinning lamellae are very thin and only visible in a microscope (fig. 7). The felspar mined for practical use is generally microcline.

Pure K-felspar has a melting point of  $1150^\circ C$ , at which temperature it is transformed to a silica-rich glass and leucite ( $K_2O \cdot Al_2O_3 \cdot 4 SiO_2$ ), a silicate that melts first at  $1530^\circ$ . In the heated quartz-rich ceramic masses leucite may not be formed at all or it may have only a brief existence. The glass of melted K-felspar has a high viscosity that diminishes only slowly with increase in temperature.

Sodium felspar or albite. The chemical formula is  $Na_2O \cdot Al_2O_3 \cdot 6 SiO_2$  corresponding to 68.8 %  $SiO_2$ , 19.4 %  $Al_2O_3$ , 11.8 %  $Na_2O$ . The colour is in most cases white, but can also be red. The albite crystallizes triclinic with an angle of  $86^\circ 24'$  between the two sets of cleavage. The albite can often be distinguished from K-felspar because of a fine or somewhat coarser striation on the cleavage plane P. The striation is caused by so called twinning whereby the felspar is built up of thin lamellae - parallel to the cleavage plane M - of which alternate ones are turned  $180^\circ$  (fig. 2 and 3).

Pure albite melts at about  $1118^\circ C$  and the felspar is then transformed to a homogeneous glass. The viscosity of albite glass is also high although lower than that of K-felspar and it diminishes more rapidly with increased temperature.

Lime felspar or anorthite. The formula is  $CaO \cdot Al_2O_3 \cdot 2 SiO_2$  which corresponds to 43.3 %  $SiO_2$ , 36.6 %  $Al_2O_3$  and 20.1 %  $CaO$ . When unaltered the anorthite is generally white, but can be red or dark. However it is often altered and hereby is a mineral formed called epidote ( $H_2O \cdot 4 CaO \cdot 3 Al_2O_3 \cdot 6 SiO_2$ ) that gives the felspar a greenish colour. The crystal system of anorthite is triclinic and the angle between the cleavages is  $85^\circ 50'$ . Twinning of a kind similar to that in albite is common.

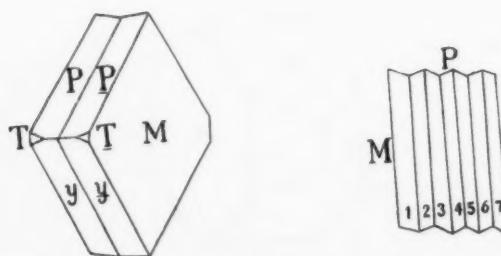


Fig. 2. Drawing, illustrating the twinning according to the albite law.



Fig. 3. Twinningstriation in plagioclase seen on the cleavage face P. About natural size.

The melting point of anorthite lies at  $1550^{\circ}\text{C}$  and the glass has a low viscosity.

Data concerning the properties of the felspars are shown in the tables 1 and 2. 1)

Table 1

	$\text{Na}$	$\text{N}\beta$	$\text{N}\gamma$	Spec. Grav.	Glass		Melting point
					N	Sp.Gr.	
K-felspar	1.519	1.523	1.526	2.54	1.487		$1150^{\circ}\text{C}$
Na- "	1.529	1.532	1.539	2.62	1.489	2.38	$1118^{\circ}\text{C}$
Ca- "	1.575	1.584	1.588	2.76	1.575	2.70	$1550^{\circ}\text{C}$

Table 2

K - f e l s p a r	N a - f e l s p a r	C a - f e l s p a r
1250 $^{\circ}\text{C}$ -log. visc. 8	1150 $^{\circ}\text{C}$ -log. visc. 8.0000	1550 $^{\circ}\text{C}$ -log. visc. 1.580
1400 $^{\circ}\text{C}$ " " 7.0094	1300 $^{\circ}\text{C}$ " " 6.0400	
1450 $^{\circ}\text{C}$ " " 6.6025	1350 $^{\circ}\text{C}$ " " 5.6381	
	1400 $^{\circ}\text{C}$ " " 5.2930*)	
	1425 $^{\circ}\text{C}$ " " 5.0752	

\*) Bowen gives for 1400 $^{\circ}\text{C}$  the figure 4.602

1) The figures for the refraction and the spec. gravity of the felspars are taken from mineralogical handbooks. For the refraction of the glass, determinations of Schairer and Bowen (Am.J.Sc., Vol. 253, 710, 1955 and Vol. 254, 158, 1956) and E.S. Larsen (ibid., Vol. 28, 270, 1909) have been used. The viscosity of the glasses is given according to determinations of F. Kani (Proc. Imp. Acad., Tokyo, 11, 1953, 334) and N. L. Bowen (Am. Geoph. Union, fifteenth ann. meeting, 1934).

## THE MISCELLIBILITY OF THE FELSPARS

The figures given in tables 1 and 2 are valid for the pure felspars. But the felspars occurring in nature are never pure, due to an extensive miscibility. On the whole there exist two series of mixtures, namely, of albite and anorthite and of albite and K-felspar. On the other hand the miscibility of K-felspar and anorthite is very restricted.

The plagioclase series. Albite and anorthite are found in nature as mixed crystals (solid solutions) of nearly all proportions. All the different members of this series are designated as plagioclases. The series is traditionally divided into subgroups according to the percentage of anorthite: albites with an anorthite content of up to about 10 %, oligoclases with about 11-30 %, andesines with about 31-45 %, labradorites with about 46-65 %, bytownites with about 66-90 % and anorthites with a higher content of Ca-felspar. In the felspar mined for ceramic uses pieces of plagioclase (generally oligoclase) are often present. The plagioclase is difficult to avoid during the separation at the mine. Ceramically this causes little trouble, unless the quantity of the plagioclase is great and its content of anorthite is high, in which case the viscosity of the glass can be too low during burning.

The melting relations of the plagioclases are simple and are shown in the diagram of fig. 4. In this the upper curve denotes the lower boundary of liquid (melted phase). The lower curve denotes the upper boundary of solids (crystals). Between the two curves is a melting interval. If for instance a plagioclase with the composition C (50 % albite and 50 % anorthite) is heated, melting begins at  $1275^{\circ}\text{C}$  and a melt of the composition D (with about 12 % Ca-felspar) is formed. As the temperature is raised the melt formed is continually richer in anorthite, until at  $1450^{\circ}\text{C}$  the last remnant of the plagioclase, with the composition B (82 % of Ca-felspar), is transformed into glass and a homogeneous melt of the composition  $\text{Ab}_{50} \text{An}_{50}$  (point A) is formed. The melting interval is in this case  $1275^{\circ}\text{C} - 1450^{\circ}\text{C}$ . Only pure albite and pure anorthite have definite melting points.

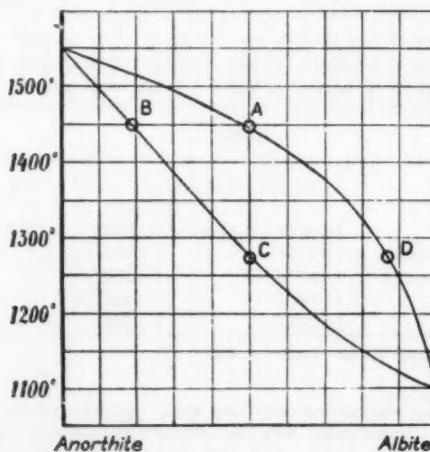


Fig. 4. Equilibrium diagram of albite-anorthite, weight percent.

**The series of potassium- sodium felspars (alkali felspars)**

The relations here are somewhat more complicated. The decomposition of K-felspar at  $1150^{\circ}$  into glass and leucite has already been named. As this decomposition probably does not occur in ceramic masses or is at most of short duration, it can here be ignored. But the miscibility of albite and K-felspar is complete only at high temperatures and becomes limited as the temperature falls. The relevant equilibrium diagram is shown in fig. 5. 1) All mixtures of albite and K-felspar are melted at temperatures over the upper unbroken curve ( $1118^{\circ}$  C -  $1150^{\circ}$  C). As shown in the diagram the melting temperature is lowered in mixtures of the two felspars and the lowest melting mixture is about 65 % albite and 35 % K-felspar. Within the area, designated as "one felspar" above and at the sides of the lower, upwards convex curve 2), we are below the melting temperature of the felspars, and albite and K-

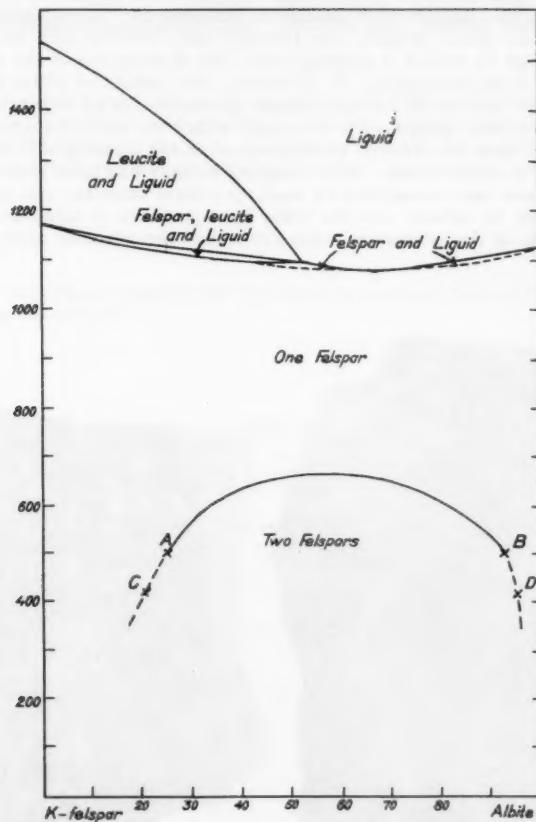


Fig. 5. Equilibrium diagram of albite and potassium felspar, weight percent.

- 1) The diagram is compiled from J. F. Schairer and N. L. Bowen, Trans. Amer. Geoph. Union, 1935 and N. L. Bowen and O. F. Tuttle, Journ. Geol., Vol. 58, 497, 1950.
- 2) The continuation of the curve at low temperatures is not determined and for this reason the extrapolated parts of it are designated with broken lines.

feldspar here form solid solutions in all proportions. The curve (named the "solvus-curve") separates an area, designated as "two felspars". Here the two felspars are not unlimitidly miscible. For example, if we choose a melted mixture with 25 % albite and 75 % K-feldspar (point A), homogeneous mixed crystals are formed at a temperature of about  $1120^{\circ}\text{C}$  and they are stable to about  $500^{\circ}\text{C}$ . If we follow the development as the temperature is lowered, the crystals become unstable just as the solvus-curve is passed and they tend to be divided in the solid state into two felspars, one of the composition A and the other of the composition B (about 92 % albite and 8 % K-feldspar). The splitting up continuess as the temperature is lowered, whereby A and B move along both sides of the curve. Thus at  $400^{\circ}\text{C}$  the composition of the two new felspars is C (80 % K-feldspar and 20 % albite) and D (95 % albite and 5 % K-feldspar) and at room temperature each feldspar can dissolve only a few percent of the other. This splitting up in the solid state of an alkali feldspar, that at high temperature forms a homogeneous crystal, is a very slow process and difficult to realize in the laboratory but in the rocks with their slow cooling and under the influence of water and pressure it has been realized to a great extent. The originally homogeneous alkali feldspar has thereby been divided into two felspars and given rise to what is called a perthite, or if the dimensions of the separated parts are very small a microperthite. If, as above, the content of albite is less than that of K-feldspar, the separated albitic feldspar generally forms thin lamellae or small parts that are crystallographically arranged within the mother feldspar. In fig. 6 two perthites of this type are shown, photographed on the cleavages P and in fig. 7 perthite is seen in a microscope. If the original feldspar had been rich in albite the K-feldspar would have been separated as small perthitic lamellae and patches, but this is relatively rare in nature. On the other hand perthitic K-felspars are very common and dominate in the occurrences that are mined for ceramic purposes.

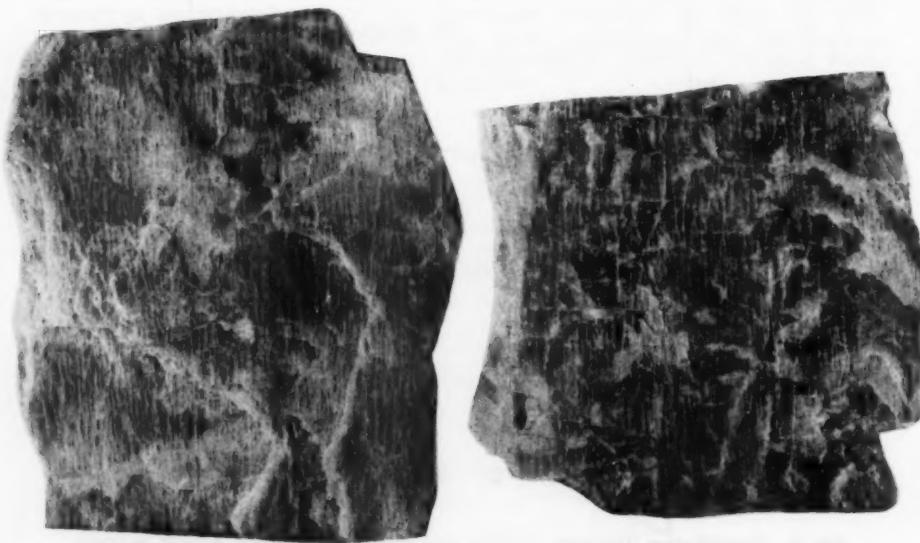


Fig. 6. Microcline-perthites, about natural size, seen on the cleavage face P. Thin vertical light stripes are albite. The light coloured irregular broader stripes and patches are caused by irregularities and fractures on the cleavage face.

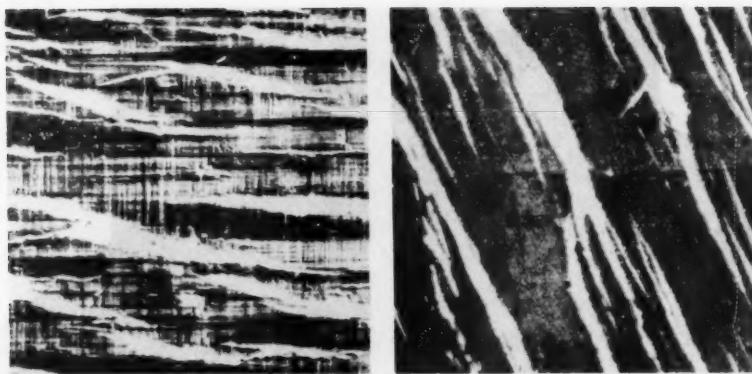


Fig. 7. Microcline-perthite, seen in a microscope, magn. about 11 x. The same felspar shown on P (left) and M (right). The broad white stripes are albite, enclosed in the dark microcline. The fine cross hatching in the left picture is due to twinning. From O. Andersen, Norges Geol. Unders. nr. 128 A.

In the glass of the alkali felspars the viscosity is lowered with increased content of albite according to table 3.

Table 3

Log. viscosity in glass at 1400°C, accord. to Kani <sup>1)</sup>

Albite 20 %, K-felspar 80 %	6.2264
" 40 %, " 60 %	5.8826
" 60 %, " 40 %	5.8046
" 80 %, " 20 %	5.6576

1) F. Kani, op. cit.

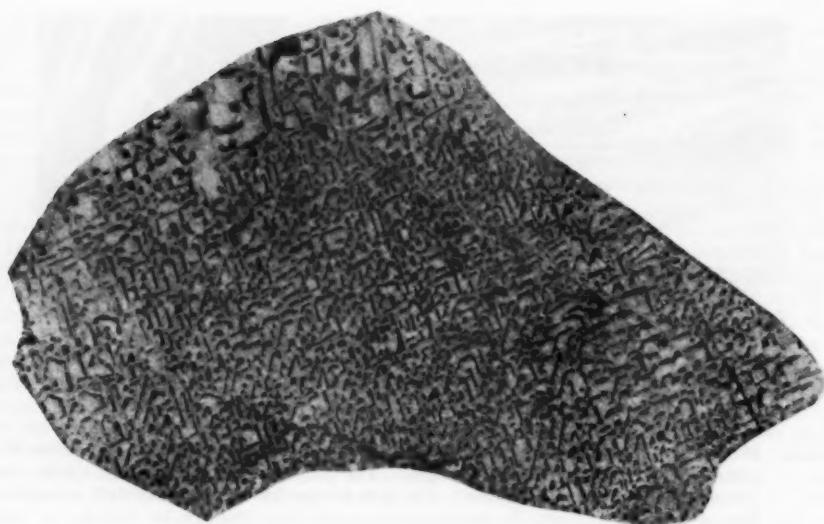


Fig. 8. Graphic granite, about natural size. The dark small cuneiform grains are quartz, white is felspar.

### PEGMATITE

Apart from Cornish Stone, the felspar in most common use in the potteries has earlier been a K-rich felspar (microcline perthite), that has been mined in so called pegmatites, and this felspar is still used, where available. Pegmatite is a rock composed of quartz, felspar and mica that are generally developed as big crystals. The same rock can also be crystallized as a fine grained mineral mixture and is then called aplite. Pegmatite and aplite generally form dykes or lenses in the rock ground. Whether or not quartz and felspar in a pegmatite can be mined, depends on the grain size of the two minerals, which must be great enough to allow a separation by hand. In certain cases the two minerals have been concentrated as separate aggregations in the pegmatite and in such cases very pure products have been obtained. However the relations very much and in most cases some quartz contamination is difficult to avoid.

Many pegmatites contain so called graphic felspar or graphic granite. In this case the quartz is intimately distributed in the felspar in the form of similarly arranged spindles, that in sections perpendicular to their long axes exhibit shapes reminiscent of cuneiform letters (fig. 8-9). Graphic felspar can be used in ceramic mixtures if it can be obtained free from iron-bearing mica but generally this is difficult. A special case of graphic felspar is offered by the Forshammar pegmatite named in the following. On an average, graphic felspar contains 70-75 % felspar and 25-30 % quartz.

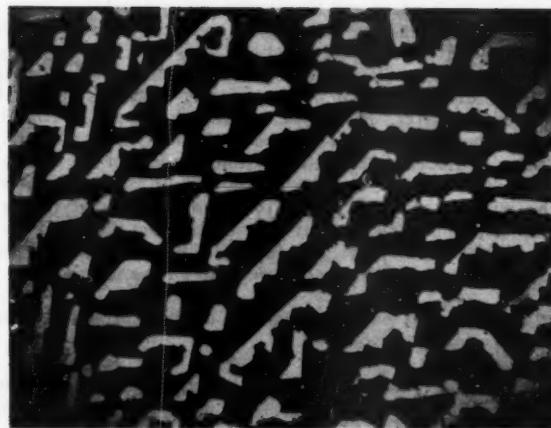


Fig. 9. The same graphic granite as in fig. 8, seen in a microscope, magn. about 16 x. White = quartz.

#### ANALYSES OF FELSPARS

##### Potassium felspar (microcline perthite) from pegmatites

The name "potassium felspar" is used in practice and the opinion may perhaps prevail that the mineral is a pure K-felspar. But all natural felspar is impure and all microcline perthites contain albite, possibly with the exception of felspars in partly kaolinized occurrences, where the albite has been decomposed before the K-felspar. The felspar mined in pegmatites for ceramic uses is a microcline perthite with a content of albite varying from 15 to 35 % by weight. A few instances of K-felspar with a content of albite lower than 15 % are known, and here belong the so-called Adularias, rare, generally clear felspar, formed at low temperatures and found, for example, in the Alps. There are also the so-called "potassium leptites" or "potassium gneisses", peculiar rocks, found at a few places in Sweden, in which the content of albite can be as low as 9 %. In these rocks the felspar is intimately and in a finely grained state mixed with quartz and dark iron - magnesium silicates from which it must be separated. The potassium leptites and -gneisses are further mentioned below.

A number of analyses of Swedish and Norwegian microperthites from pegmatites are plotted in the triangular diagrams of figs. 10 and 11, and some analyses of typical microcline perthites are reproduced in table 4. As seen in the triangles the chemical variation of the perthites is not great, and even if we added analyses of American perthites the picture would not be essentially changed. From the analyses in table 4 the quantities of quartz, K-felspar, albite and anorthite contained in the analyzed material have been calculated. In the calculation the small amounts of  $Fe_2O_3$  and  $MgO$  have been neglected. The calculation, based on the values of  $K_2O$ ,  $Na_2O$  and  $CaO$ , generally show a small surplus of alumina, in the table shown as "+ $Al_2O_3$ ". The cause of the surplus may partly be found in small analytic errors, that are difficult to avoid, but in addition small deviations from the ideal formula can exist in the minerals. If the surplus of  $Al_2O_3$  is high it is probable that the analyzed material has contained mica, which is richer in  $Al_2O_3$  than felspar.

From the calculated mineral composition the average felspar in the analyzed material has then been calculated on 100.

The analysis from Kolsva refers to felspar, produced from the mine before it was closed. "Mälar" is a product separated from the waste heaps from the earlier mining at Kolsva.

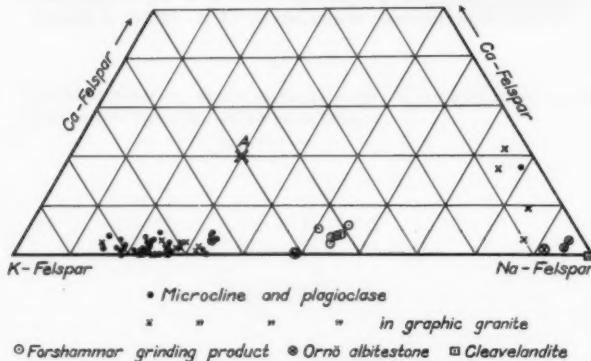


Fig. 10. Analyses of Swedish felspars, calculated in weight percent.

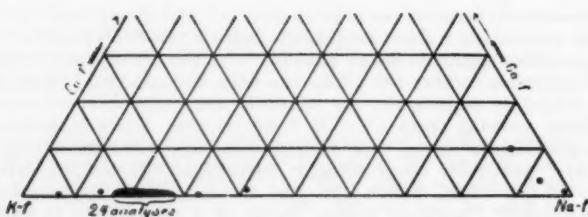


Fig. 11. Analyses of Norwegian felspars, calculated in weight percent. From O. Andersen, Norges Geol. Unders. nr. 128 A.

Table 4  
Analyses of microcline perthites from pegmatites

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Loss on ign.	Total
1. Ytterby, aver. 3 anal. 1908	64.43	19.48	0.22	0.35 <sup>1)</sup>	0.29	2.61	12.57	0.57 <sup>1)</sup>	100.52
2. " 1963	65.05	18.63	0.15	0.07	0.22	1.94	13.57	0.32	99.77 <sup>2)</sup>
3. Margretelund, 1930	64.55	19.36	0.09	0.56	2.87	12.13	9.56		
4. Kolsva, prime, 1912	65.3	19.5	0.11	0.10	0.30	3.30	11.70	0.12	100.43
5. Målar, 1954	68.38	17.36	0.27	0.07	0.20	3.59	9.50	0.40	99.81 <sup>3)</sup>
6. " 1956	69.0	18.2	0.3	0.2		2.7	9.1	0.4	99.9
7. Munkedal, 1939	65.8	18.8	0.04	0.05	0.1	2.5	12.5	0.1	99.89
8. Källaxö, about 1930	65.08	19.91	0.09	Tr.	0.12	2.36	12.22		99.90

Calculated mineral contents

	1	2	3	4	5	6	7	8
Quartz	0.52	1.33	1.44	0.68	10.71	18.49	3.20	4.31
K-felspar	74.34	80.28	71.73	60.22	56.21	53.82	73.95	72.28
Na-	22.06	16.40	24.26	27.88	30.34	22.80	21.12	19.98
Ca-	1.44	1.09	0.31	1.48	1.50	1.00	0.50	0.58
+ Al <sub>2</sub> O <sub>3</sub>	1.02			0.83	0.78	3.89	0.94	2.55

Average felspar

	75.98	82.05	74.73	70.20	64.20	70.24	77.38	77.86
K-felspar	22.55	16.77	25.27	28.28	34.65	29.76	22.10	21.52
Na-	1.47	1.17		1.52	1.14		0.52	0.62

1) Determ. only in one of the analyses. 2) Inclusive 0.02 TiO<sub>2</sub>. 3) Inclusive 0.04 TiO<sub>2</sub>.

## FORSHAMMAR

For about 30 years a pegmatite at Forshammar about 40 km N.W. of the town of Köping (at the western end of Lake Mälaren) has been mined and ground for ceramic uses. The pegmatite in the quarry consists of large crystals of graphic microcline perthite surrounded by a more fine-grained mixture of quartz, albite, microcline perthite and mica. During the mining only a small separation of unsuitable material, chiefly sparse lumps of pure quartz and varieties too rich in mica is necessary. This is because of a unique deficiency of iron in the pegmatite and because of an approximate homogeneity of the mineral mixture. The ground product contains about 34-38 % quartz, the remainder being albite, K-felspar and a restricted amount of mica. The coarse fraction of mica is sieved away during the grinding process.

A number of analyses of the Forshammar product are plotted in the diagram of fig. 10. As can be seen, the ground product shows some small variation with regard to the ratio of albite and K-felspar but it is rich in albite, having from about 51 % to 56 % albite. The analyses are accumulated in the vicinity of the lowest melting mixture of K- and Na-felspar (65 % albite and 35 % K-felspar, (comp. the diagram of fig. 5).

Analyses of the Forshammar ground product are shown in table 5. The mineral contents of the analyzed samples have been calculated in the same way, as those of the microcline perthite felspar. The  $Al_2O_3$ -surplus is here higher because of the constant presence of mica in the ground product. But the absence of iron makes the mica harmless during burning. The mica could also be calculated from the surplus of  $Al_2O_3$ , but as  $Al_2O_3$ -surplus is often found even in mica-free felspars, this calculation would be rather uncertain. The table also includes in analysis originating from a neighbouring occurrence, Limbergsbo.

Analyses of the Forshammar grinding product

Table 5

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Loss on ign.	Total
1. Analysis 1946	76.73	13.65	0.15	0.28	0.65	3.58	4.43	0.65	100.12
" 1949	75.47	14.62	0.15	0.24	0.42	3.80	4.32	0.74	99.76
2. " 1955	75.41	15.02	0.12	0.26	0.60	4.02	4.00	0.58	100.01
3. " 1957	75.92	14.16	0.18	0.27	0.41	3.85	4.45	0.59	99.83
4. " 1959	75.69	14.54	0.21	0.33	0.46	3.84	4.11	0.76	99.94
5. Limbergsbo 1951	75.93	14.29	0.11	0.20	0.23	4.06	4.76	0.46	100.04

Calculated mineral contents

	1	2	3	4	5	6
Quartz	37.6	35.9	35.5	36.9	36.7	33.7
K-Felspar	26.2	25.6	23.7	25.0	24.4	28.1
Na-	30.2	32.1	34.0	32.5	32.4	34.3
Ca-	3.2	2.1	3.0	2.0	2.3	1.1
+ Al <sub>2</sub> O <sub>3</sub>	1.8	2.9	3.0	2.3	2.9	2.1

	Average felspar					
K-Felspar	43.9	42.8	39.1	42.0	41.2	44.3
Na-	50.7	53.7	56.0	54.6	54.9	54.0
Ca-	5.4	3.5	4.9	3.4	3.9	1.7

## CORNISH STONE

As with the Forshammar pegmatite the Cornish Stone is not a felspar but a rock of white or - if it contains essential amounts of fluorspar - reddish or purple colour. It is a fine or medium grained aplite that accompanies the permian granites in Cornwall. The rock has been mined at many places. It consists of quartz, albite and K-felspar, poor in albite-perthite. In addition there is also some mica (poor in iron), fluo-spar ( $\text{CaF}_2$ ) and topaz / $\text{Al}_3\text{SiO}_4(\text{F}, \text{OH})$ /, of which the two latter are lacking in Forshammar. Chemically the rock shows considerable variations in different localities. It is further generally more or less kaolinized, often rather strongly. Analyses of Cornish Stone are shown in table 6 1) and the calculated felspar ratios are graphically shown in fig. 12. From the diagram it appears that the Cornish Stone is for the most part richer in potassium than the Forshammar grinding product and some of the analyzed samples are extremely rich in potassium. This may at least partly be due to the kaolinisation. That the kaolinisation has brought an enrichment of  $\text{K}_2\text{O}$  with it at the cost of  $\text{Na}_2\text{O}$  is indicated by the diagram in fig. 13.

The mineral contents in table 6 have been calculated, as before, from the total values of the alkalies, and the surplus of  $\text{Al}_2\text{O}_3$  arrived at in this manner has been calculated as kaolin (water-free). Unfortunately the mica cannot be determined without measurement in thin slides of the rock. The small amounts of  $\text{CaO}$  in the analyses are present in apatite and fluorite.

Cornish Stone differs from all other felspar materials by its fluorspar, which hastens the vitrifying but also attacks the lining of the kilns, and by its high content of kaolin, causing a low yield of felspar.

1) Most of the analyses have kindly been collected for this paper by Director Richard J. Bailey, Burslem, Stoke-on-Trent. Analyses 1 and 2 are reproduced from J. A. Howe, Kaolin, China-clay and China stone, Mus. pract. geology, London 1914, p. 192.

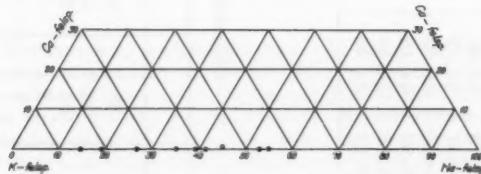


Fig. 12. Analyses of Cornish Stone, calculated weight percent of albite and K-felspar.

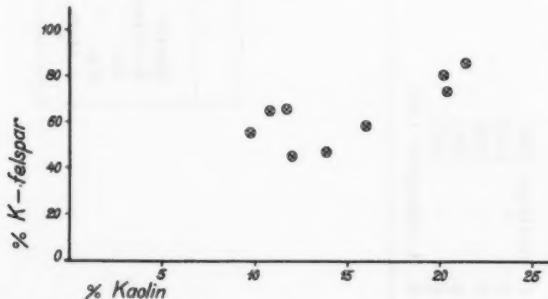


Fig. 13. Diagram showing the content of kaolin in relation to the amount of K-felspar in Cornish Stone.

Table 6  
Analyses of Cornish Stone

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	F	Loss on ign.	Total
1. Goonwean, Howe, 1914	73.18	16.13	0.52	0.14	0.61	2.18	4.41	0.23	97.87	1)
2. Goonwean, Howe, 1914	72.28	14.90	0.50	0.15	1.66	3.01	5.25	0.88	99.20	2)
3. Tr. Brit. Cer. Soc. 1913, 100	73.9	15.9	1.4	0.3	1.9	0.5	4.3		99.6	3)
4. Aver. 2 anal. Ramsden										
Monthly bull. 86, March 1935	74.0	15.5	1.5			0.75	4.5		96.25	
5. Tr. Brit. C. Soc. 1930, 258	72.9	17.3	0.25	0.04	0.8	1.3	5.2		100.19	
6. Tr. Brit. C. Soc. 1914, 100	70.3	16.6	1.5	0.1	1.5	2.6	5.7		99.7	4)
7. Aver. 2 anal. Ramsden										
Monthly bull. 86, March 1935	71.0	16.5				0.5	2.5	6.5	97.0	
8. J. Am. C. Soc. 1937, 62	72.2	16.4	0.2	0.01	2.2	3.4	4.0		99.61	
9. Tr. Brit. C. Soc. 1930, 258	72.1	16.0	0.2	0.13	2.5	2.6	3.3	1.2	98.83	

Calculated mineral contents

	1	2	3	4	5	6	7	8	9
Quartz	34.5	29.1	42.3	41.4	34.2	26.2	25.3	29.5	
K-Felspar	26.1	31.0	25.4	26.6	30.8	33.7	38.4	23.7	34.8
Na- H <sub>2</sub> O-free kaolin	18.4	25.4	4.3	6.3	11.0	22.0	21.1	28.7	19.5
	16.9	9.5	22.7	20.4	20.7	13.4	11.6	14.1	22.0
									17.7

	Average Felspar								
K-Felspar	58.6	55.0	85.7	80.8	73.7	60.6	64.5	45.2	47.1
Na- "	41.4	45.0	14.3	19.2	26.3	39.4	35.5	54.8	52.9

1) Heerin 0.02 Li<sub>2</sub>O and 0.45 P<sub>2</sub>O<sub>5</sub>. 2) Heerin 0.02 Li<sub>2</sub>O and 0.55 P<sub>2</sub>O<sub>5</sub>. 3) Heerin 0.3 TiO<sub>2</sub> 4) Heerin 0.2 TiO<sub>2</sub>

## POTASSIUM LEPTITE, POTASSIUM GNEISS

In a few localities in Sweden peculiar rocks have been found which because of their mineral composition have been named potassium leptite or, when coarser grained, potassium gneiss. The rocks are fine- or medium grained and of red or greyish red-brown colour. The best known occurrence is Bötsholmen in Stockholm's archipelago. The chief mineral is a microcline, low in albite perthite, and the rock contains 5-10 % quartz and essential amounts of dark mica (biotite), sometimes also amphibole and sparse grains of iron ochre. On Bötsholmen the dark minerals are mainly biotite and tourmaline and the rock here is unusually rich in light mica, that can contain some sillimanite ( $Al_2O_3 \cdot SiO_2$ ). Magnetic separation or flotation is necessary to isolate felspar from the rock. As yet only small scale attempts have been made. Two analyses of separated samples are shown in table 7.

Table 7

## Felspar, separated from potassium gneiss

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Loss on ign.	Total
1. Bötsholmen 1954	76.10	12.94	0.18	0.04	0.07	0.88	9.75		99.96
2. Bötsholmen 1956	70.2	16.9	0.3	Tr.	Tr.	1.2	11.1	0.2	99.9

Calc. mineral contents			Average felspar		1	2
	1	2				
Quartz	33.5	20.7				
K-felspar	57.7	65.7	K-felspar		88.1	86.6
Na- "	7.4	10.2	Na- "		11.4	13.4
Ca- "	0.3		Ca- "		0.5	
+ Al <sub>2</sub> O <sub>3</sub>	0.9	2.9				

## ALBITE STONE FROM ORNÖ

A very pure albite stone has been found at two localities on Ornö in Stockholm's archipelago at Kyrkviken on the eastern side of the island and at Skinnardal at its western side. A considerable quantity of stone has been mined at Kyrkviken, which is the larger occurrence. The stone is a white or pink aplite, low in quartz. It is generally low in potassium, but the ratio of Na- to K-feldspar has sometimes been intermediate. Two analyses of rather pure albite stone are shown in table 8.

Table 8

## Albite Stone from Ornö

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Loss on ign.	Total
1. Lugnet, Ornö	66.69	21.39	0.08		0.25	10.39	1.19		99.99
2. Skinnardal, Ornö	67.97	19.61	0.06	0.00	0.59	10.74	0.43	0.17*)	99.57

\*) Det. as H<sub>2</sub>O

	Calc. mineral contents		Average felspar			
	1	2	1	2	1	2
Quartz	1.3	2.9				
K-feldspar	7.0	2.6	K-feldspar		7.3	2.7
Na- "	87.8	90.8	Na- "		91.4	94.7
Ca- "	1.3	2.5	Ca- "		1.3	2.6
+ Al <sub>2</sub> O <sub>3</sub>	2.6	0.6				

## CLEVELANDITE

A very pure albite is often present in pegmatites. It has a characteristic tabular form and has been given the name Cleavelandite, but it is not generally abundant and concentrated enough to be mineable. An analysis of Cleavelandite is represented in the triangle of fig. 10.

THE THERMODYNAMIC PROPERTIES  
OF MIXTURES OF QUARTZ AND FELSPAR

In a ceramic body the felspars are mixed with quartz and this brings about a considerable lowering of the melting temperature. We have to distinguish between two different cases, firstly when the felspar is only an alkali felspar or nearly so and secondly when noteworthy amounts of calcium felspar are admixed. In the former case quartz, soda- and K-felspars form, together with a little  $Al_2O_3$ , eutectic mixtures with the following properties. 1)

Eutectic of quartz-albite- $Al_2O_3$ ,  $Na_2O = 7.8$ ,  $Al_2O_3 = 13.5$ ,  $SiO_2 = 78.7\%$  or  $65.9\%$  albite,  $33.4\%$  quartz,  $0.7\%$   $Al_2O_3$ . Melting temperature  $1050^{\circ}C$ . 2)

Eutectic of quartz-K-felspar- $Al_2O_3$ ,  $K_2O = 9.5$ ,  $Al_2O_3 = 10.9$ ,  $SiO_2 = 79.6\%$  or  $56.2\%$  K-felspar,  $43.2\%$  quartz and  $0.6\%$   $Al_2O_3$ . 3) Melting temperature  $985^{\circ}C$ .

In mixtures of albite and K-felspar + quartz as always is the case in ceramics, the melting temperature is even lower. Exact determinations are wanting as yet but the lowest melting temperature may be that of a mixture containing about  $60\%$  albite and  $40\%$  K-felspar.

If lime felspar (anorthite) is present together with alkali felspars the influence from the former may be different if the alkali felspar present is dominantly K-felspar or if albite is present in large amounts. This will be clear from the following.

Anorthite + albite + quartz. When heated together the two felspars form solid solutions (plagioclases, comp. p. 6). The eutectic of albite and quartz melts at  $1062^{\circ}C$ . 4) The corresponding temperature for the eutectic of anorthite and quartz is  $1368^{\circ}C$ . 5) Mixtures of quartz and plagioclases form eutectics with intermediate melting points. An admixture of anorthite to an albite-quartz mixture therefore results in an increase in melting temperature.

In the case of K-felspar the relations are different. K-felspar and quartz form together with a small quantity of anorthite a eutectic with a melting temperature of about  $950^{\circ}C$ , which is the lowest melting eutectic determined in felspar-quartz-mixtures with pure felspar (J. F. Schairer and N. L. Bowen, Bull. Soc. de Finland, 20, 75, 1947). Its composition is about  $41.4\%$  quartz,  $56.9\%$  potash felspar and  $1.7\%$  anorthite. Thus the quantity of anorthite necessary to form this eutectic is rather small.

---

- 1) J. F. Schairer and N. L. Bowen, Am. J. Sc., Vol. 253, 1955 and 254, 1956.
- 2) When calculated on the minerals stable at the melting temperature the mineral composition is  $65.9\%$  albite,  $33.2\%$  tridymite and  $0.9\%$  mullite.
- 3) When calculated on the minerals stable at the melting temperature  $56.2\%$  potash felspar,  $43.0\%$  tridymite and  $0.8\%$  mullite.
- 4) J. F. Schairer and N. L. Bowen, Am. J. Sc., Vol. 254, 1956. The composition of the eutectic is  $68.5\%$  albite and  $31.5\%$  quartz.
- 5) J. F. Schairer and N. L. Bowen, Bull. de la Soc. Géol. de Finland, Vol. XX, 71, 1947. The composition of the eutectic is  $50.5\%$  anorthite and  $49.5\%$  quartz.

## SOME EXPERIMENTS REGARDING THE EFFECT OF DIFFERENT FELSPARS IN CERAMIC BODIES 1)

### The influence of albite

In a ceramic body most of the quartz and felspar are mixed as a fine powder together with kaolin. During burning the minerals in the powder begin to react with one another and tend to form a glass of the composition of the lowest melting mixture attainable with regard to the mineral composition of the body. Equilibrium will certainly not be reached in the body because the chemical reaction in the ceramics do not have enough time to reach equilibrium on account of the speed of the heating. But the melting temperature of the eutectic of quartz and felspar which is possible in the ceramic is of decisive importance for the beginning and progress of melting and glass-building. The kind of felspar is therefore of importance for the vitrifying ability of the body.

On the other hand the thermodynamic properties of the quartz-felspar- $\text{Al}_2\text{O}_3$ -eutectics do not alone determine the rate of glass building. The viscosity of the newly formed glass also plays an essential role. A tough and viscous glass renders the diffusion difficult and causes the reactions to develop slowly while a low viscosity hastens the reactions and the glass building. As seen in the above the K-felspar produces a very viscous glass. Albite glass has a lower viscosity but it is high enough to prevent a deformation of the obstacles in the kiln up to rather high temperatures.

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1) This and the next following chapter are mainly a summary of two papers, published by N. Sundius and H. Nordgren in *Trans. British Ceram. Soc.*, Vol. 55, p. 177, 1956 and Vol. 58, p. 224, 1959.

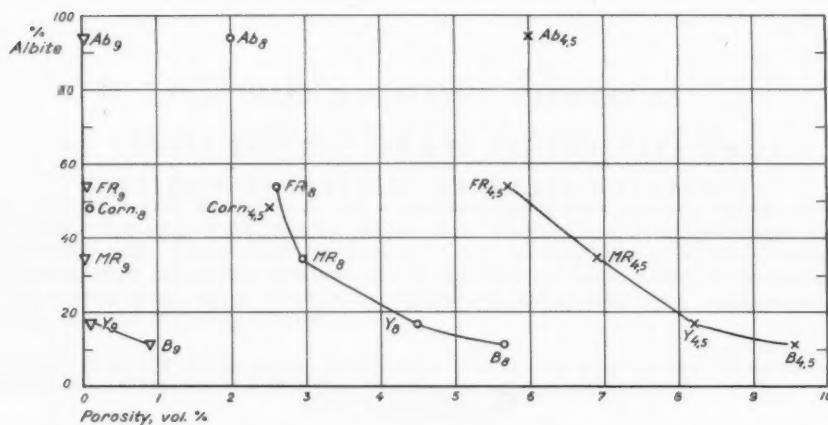


Fig. 14. Diagram of porosity and albite content. B = Bötholmen, K-felspar = 88.1, albite = 11.4, anorthite = 0.5; Y = Ytterby, K-felspar = 82.1, albite = 16.8, anorthite = 1.1; Mälar, K-felspar = 64.2, albite = 34.7, anorthite = 1.1; Fr = Forshammar, K-felspar = 43.7, albite = 54.1, anorthite = 2.2; Ab = albite stone from Ornö, K-felspar = 2.7, albite = 94.3, anorthite = 3.0; corn = Cornish Stone. The figures by the letters refer to the cone of firing.

In fig. 14 the results of some experiments with ceramic bodies, made with different alkali felspars are shown graphically.<sup>1)</sup> The body is in all cases similar (50 % clay, 25 % felspar, 25 % quartz) but the kind of felspar varies in the different samples, from an extreme K-felspar with only 11.4 % albite to nearly pure albite. From the two series of points corresponding to samples burnt at cone 4.5 and 8 the porosity is seen to diminish continually down to the sample with 55 % albite (FR, albite: K-felspar about 55 : 45). The diminished porosity implies that the amount of glass has increased and that it has more effectively flown together. The curves for the two cones are in accordance with the thermodynamic properties of the different felspars, as treated above, but also with the diminution of the viscosity of the glass produced by the albite. Probably both effects cooperate to determine the shape of the curves. On the other hand the sites of the points representing nearly pure albite (Ab) are not consistent with its thermal properties. According to them the two points Ab<sub>4.5</sub> and Ab<sub>8</sub> should lie to the right of B<sub>4.5</sub> and B<sub>8</sub>. This discrepancy may be the result of the relatively low viscosity of the albite-quartz glass, somewhat accentuated by the small content of anorthite in the albite. The probable development in the body with albite may have been that melting and glass building have begun after a longer time in the kiln than in the case of the potassium-bearing samples, but because of the low viscosity of the albite-quartz glass the vitrifying has afterwards been hastened.

In the diagram, points are also shown corresponding to samples with Cornish Stone (Corn<sub>4.5</sub> and Corn<sub>8</sub>). The site of the points illustrates the strong fluxing effect of the fluorite present in this felspar.

1) N. Sundius and H. Nordgren, Op. cit., p. 184, 1956.

## INFLUENCE OF LIME

The influence of lime is similar to that of anorthite because the lime during burning reacts together with  $Al_2O_3$  and  $SiO_2$  in the proportions of anorthite. The influence is of two kinds, firstly in that the anorthite forms a low melting eutectic with quartz and K-felspar (comp. above) and secondly in that the viscosity of the glass produced in the body is strongly reduced by the presence of anorthite. The latter effect is of great importance and explains the far reaching homogeneity of the body in lime-admixed ceramics.

In an ordinary felspar porcelain not containing lime, all the felspar, even the coarse grains, is melted when the burning reaches about cone 8 or 9. But the newly formed felspar glass is very viscous and the coarser grains retain their form. The felspar glass becomes mixed with mullite needles as the temperature is raised but the angular form of the grains is well preserved even at high temperatures (fig. 18). If lime is admixed in the body the felspar is melted as above but on account of the low viscosity of the glass the melted substance from the coarse felspar grains is spread out in the groundmass of the ceramic, the result being a homogeneous, dense and glass-rich porcelain (fig. 19), in which small remnants of quartz grains are left as relics of the original constituents. The quartz too is more strongly attacked than in a lime-free ceramic and sometimes it is almost completely dissolved. This homogeneous consistence is reached about contemporaneously with a dense character of the objects or at a little higher temperature.

Fig. 15 shows the result of some experiments made with admixtures of chalk ( $CaCO_3$ ). The alkali felspars used for the bodies were the same as in the tests reported in fig. 14, only no experiment was made with pure albite. Thus the content of potassium was very high in the bodies containing Bötholmen felspar (only 11.4 % albite in the felspar) and intermediate in those with the MR-felspar (about 34.7 % albite in the felspar) whereas the Forshammar felspar contained about 54 % albite and 44 % K-felspar. The composition of the test bodies was the same as in the foregoing experiments, 50 % clay 25 % felspar and 25 % quartz. In each series 1.25, 2.5 and 5 % of the different felspars were subtracted and exchanged for 0.43, 0.86 and 1.72 % chalk ( $CaCO_3$ ). These are the quantities of  $CaCO_3$  that can be expected to form the same amounts of anorthite during burning as those of the subtracted alkali-felspars. Thus the sum of felspar in the bodies is maintained constant at 25 %.

The strong fluxing influence of the lime admixture can be seen from the diagrams, by comparing the sites of the points for the pure felspar porcelains plotted on the bottom lines of the diagrams, with those for the porcelains mixed with lime. Furthermore there is an evident difference in the reaction of the different felspars to the added lime-substances. The effect of the lime is on the whole greatest in the samples with the potassium-rich Bötholmen felspar. In the case of MR a diminution of the vitrifying ability occurs with 1.72 % chalk at cone 4.2 and this behaviour is even more apparent in the diagram of the albite-rich Forshammar tests. Therefore the quantity of chalk that should be added in order to hasten the vitrifying of a felspar porcelain can be greater in the case of a K-rich felspar than in that of an albite-rich sample. On the whole the quantity of lime needed is not great.

This different behaviour of the two alkali felspars is consistent with their experimentally determined properties. When K-felspar is mixed with anorthite a low mel-

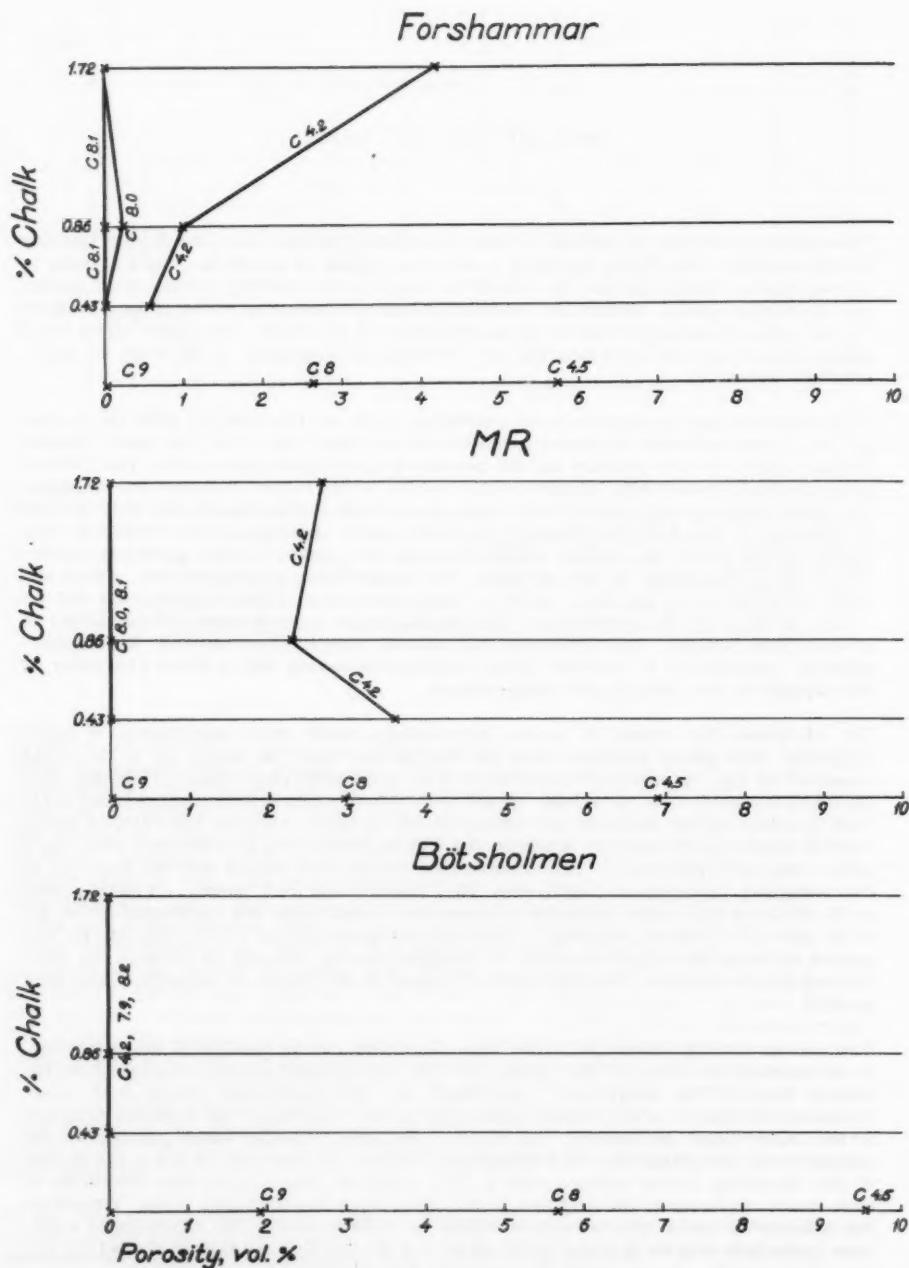


Fig. 15. Diagram of porosity and varying admixtures of chalk in test bodies containing different felspars. Regarding the composition of the felspars see fig. 14.

ting eutectic is formed (comp. above) and a surplus of anorthite may be dissolved, to a certain extent, as the temperature is raised and the burning prolonged. This diminishes the viscosity and hastens the vitrifying.

On the other hand, if a felspar rich in albite is mixed with anorthite the albite reacts otherwise. An anorthite-K-felspar-quartz eutectic is certainly formed and some albite is probably dissolved in it but if a surplus of anorthite is present it tends to enter into the remaining albite and form an anorthite bearing plagioclase. Its melting point is higher than that of albite and the plagioclase dissolves more slowly in the glass.

### THE INFLUENCE OF MAGNESIUM — AND BARIUM CARBONATE

Small amounts of  $MgCO_3$  and  $BaCO_3$  are often used as fluxes in felspar ceramics. Theoretically the effect of  $MgCO_3$  depends on the ability of small amounts of  $MgO$  to form a low melting eutectic with  $K_2O$ ,  $Al_2O_3$  and  $SiO_2$ .<sup>1)</sup> Regarding mixtures of  $MgO$  and albite no relevant experiments seem to have been made but in all cases  $MgO$  behaves differently from  $CaO$  in this connection. It does not form an aluminum-silicate of similar type as anorthite that dissolves in albite during burning and raises the vitrifying temperature.

In the case of  $BaO$  relevant laboratory experiments seem to be lacking.

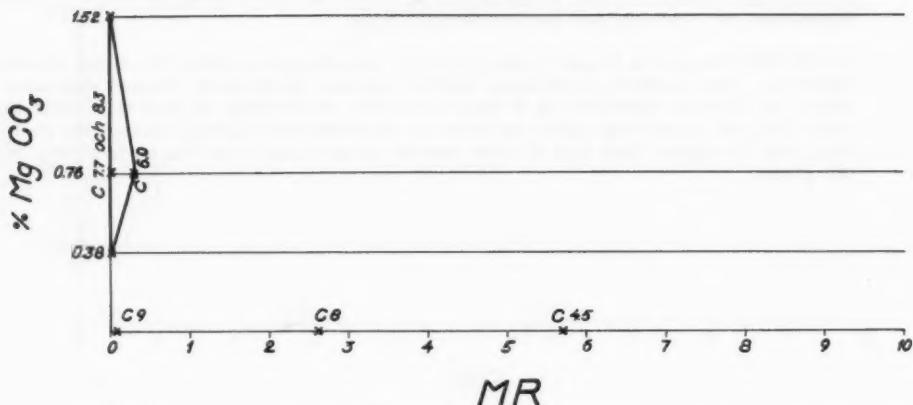
Both  $MgO$  and  $BaO$  diminish the viscosity of the glass in the body and, to judge from the consistency of the test bodies when seen in slides in a microscope, the effect is rather similar to that of  $CaO$ . Fig. 19-21 show the similarity of three specimens containing the same molecular admixtures of the three oxides and burnt at about the same temperature.

Fig. 16-17 show graphically the results from some tests made on samples with admixtures of  $MgCO_3$  and  $BaCO_3$ . The admixtures are of the same molecular quantities as in the tests with  $CaCO_3$ , and the same alkali felspars have been used as in the foregoing cases. As seen in the diagrams the fluxing effect at the cones used is rather similar as that for  $CaO$ .

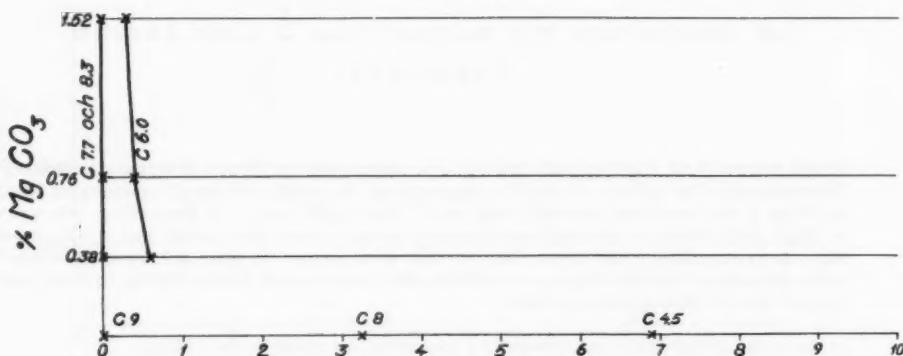
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1) Equilibrium diagram of J. F. Schairer, Am. J. Ceram. Soc., 37, 506, 1954.

## Forshammar



MR



Bötsholmen

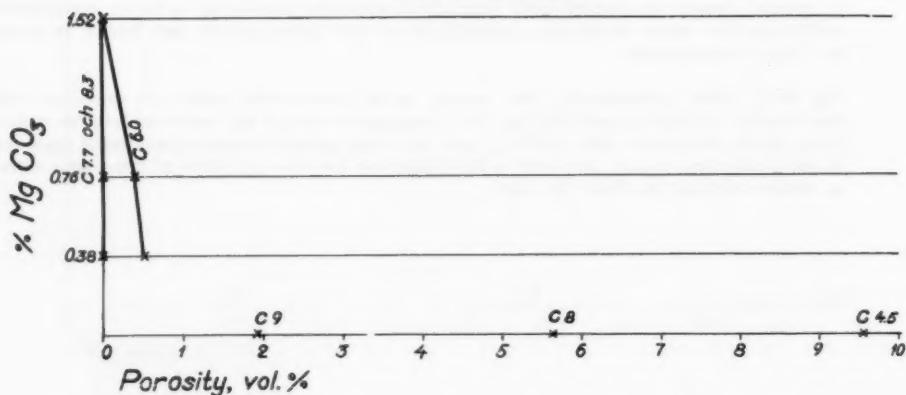


Fig. 16. Diagram of porosity and varying admixtures of  $\text{MgCO}_3$ .  
Regarding the composition of the felspars see fig. 14.

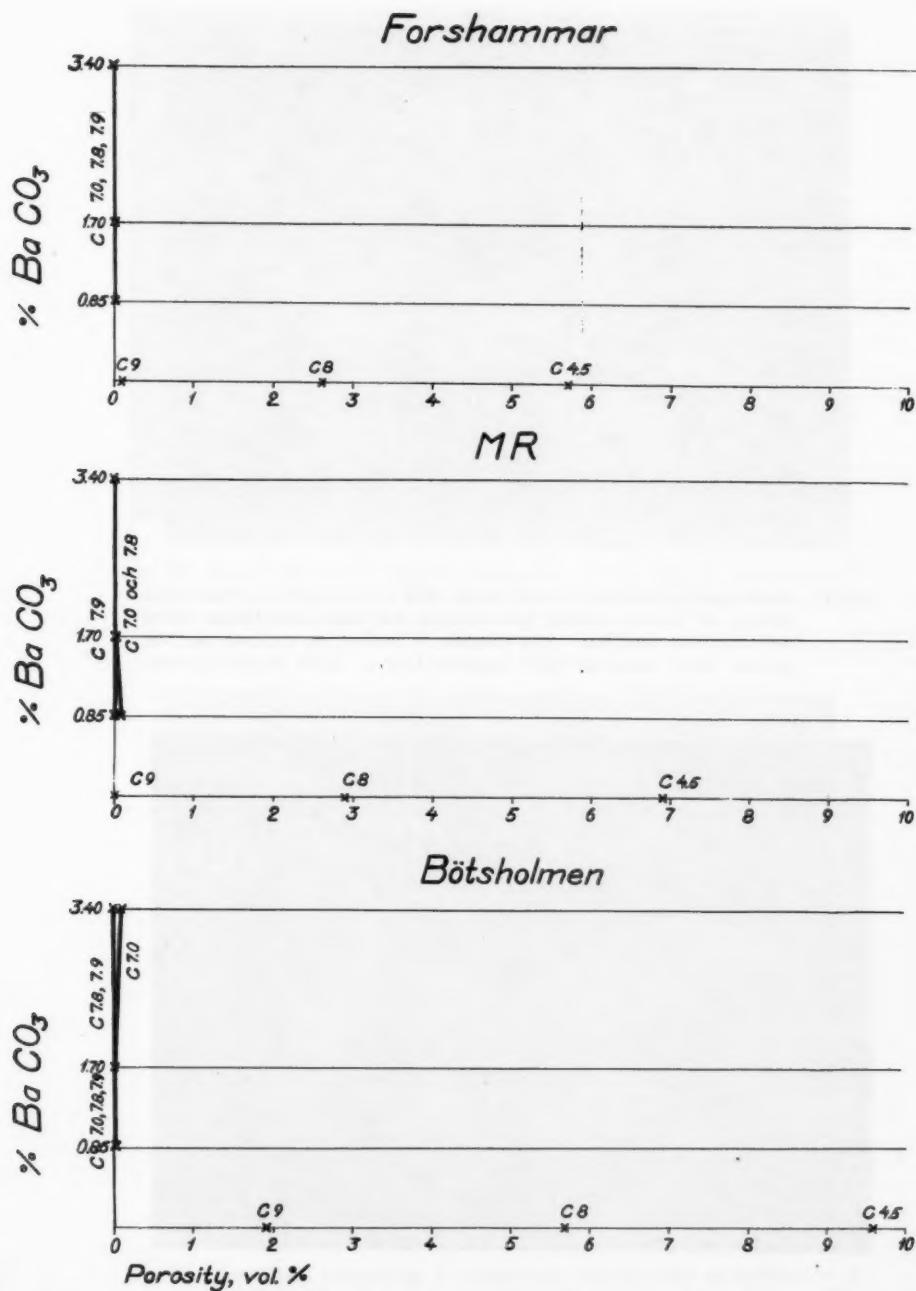


Fig. 17. Diagram of porosity and varying admixtures of  $BaCO_3$ .  
Regarding the composition of the felspars see fig. 14.

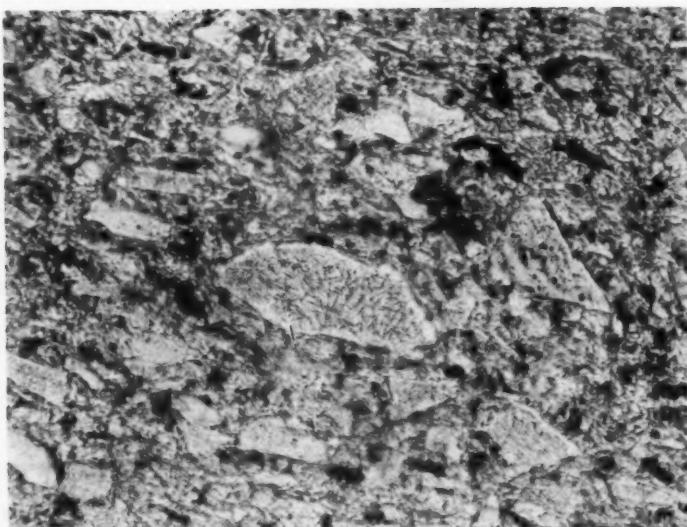


Fig. 18. Electrical porcelain, Locke, magn. 350 x, cone 10-11. Numerous grains of quartz (white) and feldspar are seen, the latter filled with mullite needles. The feldspar is melted to a glass but the grains have retained their angular form. Dark spots = pores.

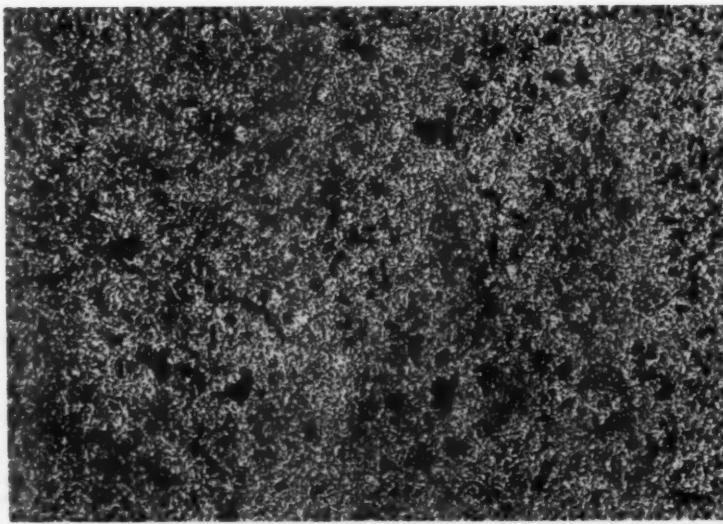


Fig. 19. Test body containing Forshammar feldspar and an admixture of 0.86 % chalk, burnt at cone 8.1 in bone kiln. Magn. 280 x. The body is rich in glass and homogeneous in consistency.

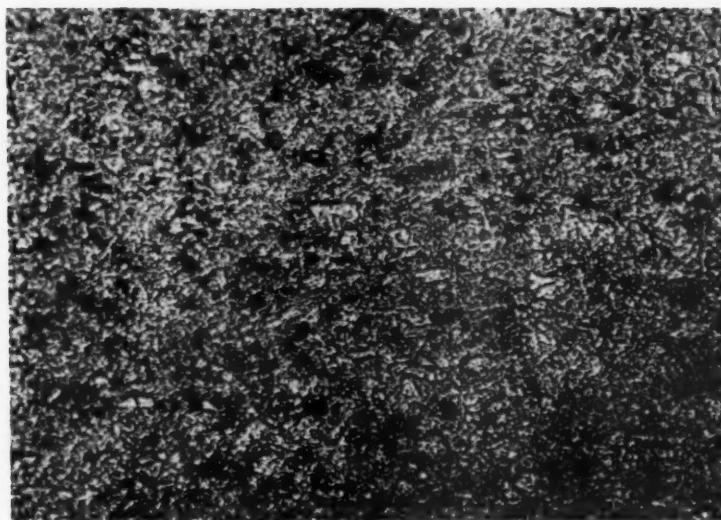


Fig. 20. Test body containing Forshammar felspar and an admixture of 0.76 %  $\text{MgCO}_3$ , burnt at cone 8.3 in bone kiln. Magn. 280 x. The consistency similar to that in fig. 19.



Fig. 21. Test body containing Forshammar felspar and an admixture of 1.7 %  $\text{BaCO}_3$ , burnt at cone 7.8 in bone kiln. Magn. 280 x. The consistency similar to that in fig. 19 and 20.





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